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Phenomenology of Superstrings^{1,2}

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Abstract

We consider the low energy phenomenology of superstrings. In particular we analyse supersymmetry breaking via gaugino condensate and we compare the phenomenology of the two different approaches to stabilize the dilaton field. We study the cosmological constant problem and we show that it is possible to have supersymmetry broken and zero cosmological constant. Finally, we discuss the possibility of having an inflationary potential. Requiring that the potential does not destabilize the dilaton field imposes an upper limit to the density fluctuations which can be consistent with the COBE data.

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INTRODUCTION

Superstrings offers the exciting possibility of predicting all the parameters of the standard model in terms of a single parameter, the string tension. However in order to realize the full predictive power of the superstring it is necessary to determine the origin and effects of supersymmetry breaking. Only after SUSY is broken are the vacuum expectation values (vevs) of moduli determined and these determine the couplings of the effective low energy theory. Also SUSY breaking must be responsible for the splitting of supermultiplets allowing for the superpartners to be heavier than their standard model partners.

The dilaton field S plays a crucial role since it interacts with all scalar fields and has a generic interaction. In the context of gaugino condensate [1] it is the dilaton field that sets the mass hierarchy. Its auxiliary field may be responsible for breaking SUSY in which case the soft supersymmetric breaking terms are universal. Furthermore, the dynamics of the dilaton field does not allow for the scalar potential V to inflate [2], [3] and therefore S must be at its minimum before the universe expands rapidly. Clearly, a potential must be positive to inflate. Is it then possible to have S stable and $V > 0$?

Due to lack of space we will just give a short presentation of the different possibilities to stabilize the dilaton field and a discussion of some phenomenological consequences, vanishing of the cosmological constant and inflation. Unfortunately, we will not be able to talk about many interesting topics like S duality, fermion masses, the strong CP problem, discrete and accidental symmetries and the phenomenology of light scalars and axions.

DILATON FIELD AND SUSY BREAKING

In the absence of non-perturbative effects, the dilaton field interacts with all scalar fields with an $1/S$ interaction, and the scalar potential does not have a stable solution. There are several possibilities to stabilize the dilaton. Firstly, one can impose an S -duality[4] (analogous to the T dual symmetry) invariance to

the potential. Another possibility is to consider gaugino condensation. Gaugino condensation [1] offers a very plausible origin for SUSY breaking for it is very reasonable to expect such a condensate to form at a scale between the Planck scale and the electroweak breaking scale if the hidden sector gauge group has a (running) coupling which becomes large somewhere in this domain. Non-perturbative studies in effective supergravity theories resulting from orbifold compactification schemes suggest the dynamics of the strongly coupled gauge sector is such that the gaugino condensate will form and trigger supersymmetry breaking.

Using symmetry and anomaly cancelation arguments one derives an effective superpotential for the gaugino condensate $\langle \bar{\lambda}_L \lambda_R \rangle$ in terms of S

$$W_0 = d(T) e^{-3S/2b_0} \simeq \Lambda_c^3$$

where Λ_c is the condensation scale. The scalar potential is given by $V_0 = e^K |W_0|^2 [(1 + \frac{3S_r}{2b_0})^2 - 3] = | \langle \bar{\lambda}_L \lambda_R \rangle |^2 \frac{b_0^2}{36} [(1 + \frac{3S_r}{2b_0})^2 - 3]$ and it does not have a stable solution. There are two different approaches to stabilize the potential:

(I) Consider two gaugino condensates [5] and chiral matter fields with non-vanishing v.e.v. and slightly different one-loop beta function coefficients $b_0^1 \simeq b_0^2$ with a superpotential

$$W_0 = d_1 e^{-3S/2b_0^1} - d_2 e^{-3S/2b_0^2}.$$

A stable solution is found for vanishing auxiliary field of the dilaton $G_S = W_S - W/S_r \simeq \frac{\partial W_0}{\partial S} = 0$. SUSY will then be broken by the auxiliary field of the moduli field G_T .

(II) Consider loop corrections of the 4-Gaugino interaction "à la N-J-L" using the Coleman-Weinberg one-loop potential V_1 . A stable solution is found for $V = V_0 + V_1$ with a single gaugino condensate [6]. The leading contribution to V_1 is given by the gaugino mass m_g and since $m_g^2/\Lambda_c^2 \ll 1$ one has $V_1 \simeq -\frac{n_g}{32\pi^2} \Lambda_c^2 m_g^2$ where n_g is the dimension of the hidden gauge group. The scalar potential $V =$

$V_0 + V_1$ can then be written as

$$\begin{aligned} V &\simeq e^K \left[|h|^2(1 - \delta F_S^2) + |h_T|^2(1 - \delta |F_T|^2) - 3|W|^2(1 + 3\delta) - \delta A \right] \\ V &\simeq e^K \left[|h|^2 + |W|^2 \left(\frac{3T_r^2}{4\pi^2} |\hat{G}_2(T)|^2(1 - F_T^2\delta) - 3(1 + 3\delta) \right) - \delta A \right] \end{aligned} \quad (1)$$

with $A \equiv h_S \bar{h}_T - 3\bar{W}(F_S + F_T) + h.c.$, $h = S_r G_S = S_r W_S - W = F_S W$, $h_T = \sqrt{3} T_r G_T = F_T W$, $F_S = -(1 + \frac{3S_r}{2b_0}) \gg 1$, $F_T = \sqrt{\frac{3T_r^2}{4\pi^2}} \hat{G}_2(T)$ and $\delta \equiv \frac{n_g b_0^2}{144\pi^2} \ll 1$. We recover the tree level potential by setting $\delta = 0$.

Results

Let us now compare the results obtained by minimizing the scalar potential in the case of two gaugino condensates (I) and for the case of one gaugino condensate (II). In both cases a large hierarchy can be obtained.

(I) 2 gaugino condensates	(II) 1 gaugino condensate
$\langle S \rangle \simeq 0.17 \frac{N_2 M_1 - N_1 M_2}{(3N_2 - M_2)(3N_1 - M_1)}$	$\langle S \rangle \simeq \frac{4\pi}{\sqrt{n_g}}$
$\langle T \rangle \simeq 1.2$	$\langle T \rangle \simeq \frac{3S_r}{2\pi b_0(1-\alpha_0)} \simeq O(10 - 20)$
$m_{3/2} = O(1) TeV$	$m_{3/2} = O(1) TeV$
$G_S = 0, \quad G_T \neq 0$	$G_S \gg G_T$

where $b_i = \frac{1}{16\pi^2}(3N_i - M_i)$, α_0 is related to the number and weight of the hidden sector fields (for an orbifold with untwisted fields only $\alpha_0 = -1/3$) and G_S, G_T are the auxiliary fields of the dilaton and moduli fields respectively. All the parameters are related to the normalization and number of fields of the hidden sector and are fixed for a given compactification scheme. Note that the v.e.v. of the moduli in case (II) are much larger than in case (I).

The phenomenology depends strongly on which auxiliary field breaks SUSY and in case (I) SUSY is broken due to the auxiliary field of the moduli G_T while in case (II) it is mainly due to the auxiliary field of the dilaton $G_S \gg G_T$. The soft supersymmetric breaking terms are universal if SUSY is broken via G_S while they differ if SUSY is broken via G_T and they have been calculated in

[6],[7]. Experimental evidence on the neutron dipole momenta show that the scalar masses must be almost degenerated $((m_1^2 - m_2^2)/m^2 < 10^{-2} - 10^{-3})$.

UNIFICATION SCALE AND COUPLING

We will, now, discuss the unification scale and coupling. The fine structure constant at the unification scale is $\alpha_X^{-1} \simeq \frac{4\pi}{g_{gut}^2} \simeq 4\pi Re S$ and using the solutions of minimization for case (II) we have [8]

$$\alpha_X^{-1} \simeq \frac{16\pi^2}{\sqrt{n_g}}. \quad (2)$$

Consistency with MSSM unification [9] requires then $33 < n_g < 44$ and this is satisfied only for the gauge groups $SU(6)$ or $SO(9)$ ⁴. In case (I) there are more possibilities to obtain a fine structure constant required by MSSM unification and the gauge group is therefore not constraint. However, MSSM unification also imposes constraint on the value of the unification scale. The unification scale M_X is a moduli dependent function with the property to be close to the string scale for $T \simeq 1$. On the other hand if T is larger then there is the possibility of having $M_X \simeq 10^{16}$ as required [9]. As an example we can take an $SU(6)$ with $b_0 = 15/16 \pi^2$ for which $T = 22$, the unification fine structure constant and scale are $\alpha_X^{-1} = 26.1$, $M_X = 2.8 \times 10^{16} GeV$.

COSMOLOGICAL CONSTANT

The vanishing of the cosmological constant is an important and still open problem. Experimental evidence shows that the cosmological constant is very small and it is not clear how to implement it a natural scheme. Another approach, is to study the possibility of having a potential with vanishing cosmological constant by introducing new terms and fine tuning them. In non-supersymmetric models this represents no problem. However, in SUSY potentials the possible terms are constraint. In fact, for global supersymmetry it is not possible, if one requires

⁴Considering only $SU(N)$ and $SO(N)$ gauge groups.

SUSY to be broken (spontaneously or explicitly). On the other hand, in sugra models one has, in principle, the possibility of having $V=0$ and SUSY spontaneously broken (SB). The breaking of SUSY is a necessary condition but for the simplest potentials if a symmetry is SB the vacuum energy will then be proportional to the symmetry breaking scale (Λ), $V = -O(\Lambda^4)$. For realistic hierarchy solution $V \simeq -(10^{-12})^4$ which is many orders of magnitude larger than the observational upper limit $|V| < 10^{-120}$. In the context of supergravity models, the canceling of the cosmological constant must come through a non-vanishing value of an auxiliary field $G_i \neq 0$.

The condition of zero cosmological constant, considering the tree level potential only, is $G_a(K^{-1})^a_b G^b = 3|W|^2$ but it is hard to satisfy dynamically. Imposing T -duality symmetry and assuming, for simplicity, that the T dependent part of the superpotential can be factorized we have $W = \eta(T)^{-6}\Omega(S, \phi)$ with $\Omega = \Omega_0(S) + \Omega_{ch}(\phi)$ and Ω_0 the contribution from the gaugino condensates while Ω_{ch} the contribution from the chiral matter fields. The scalar potential becomes [10]

$$V_0 = e^K |\eta|^{-12} \left[|h|^2 + |k|^2 + |\Omega|^2 \left(\frac{3T_r^2}{4\pi^2} |\hat{G}_2(T)|^2 - 3 \right) \right] \quad (3)$$

where \hat{G}_2 is the Eisenstein function of modular weight 2, $h = S_r \Omega_S - \Omega$ and $k \equiv K_i \Omega + \Omega_i$.

To find the vacuum state with zero cosmological constant one needs to solve the eqs. $V| = V_S| = V_T| = V_i| = 0$ where “ $|$ ” denotes that the quantities should be evaluated at the minimum. $V| = V_T| = 0$ is satisfied for T at the dual invariant points ($T = 1, e^{-\pi/6}$) where $\hat{G}_2 = 0$. This implies that the auxiliary field of the moduli is zero, $G_T = 0$, and it does not break SUSY contrary to case (I) where the condition $V| = 0$ was not imposed. The cancelation of the cosmological constant must then be due to h or k . In the absence of k , for the two gaugino condensates case, the solution to $V_S = 0$ is $h = 0$ and therefore the condition $V| = 0$ must be due to k . However, if all superpotential terms Ω_{ch} are at least quadratic in ϕ_i then $k = 0$ for $\phi_i = 0$. The only possibility to have $k \neq 0$ is with a linear superpotential $\Omega_{ch} = c\phi$, where c is an arbitrary constant to be fine

tuned to give $V| = 0$. Let us take the example $N_1 = 6, M_1 = 0, N_2 = 7, M_2 = 6$. For this example one obtains a large hierarchy and $S = 2.16$ if $k = 0$ [5]. The numerical solution to $V| = V_S| = V_\phi| = 0$ is $S = 2.15, c = 1.2 \times 10^{-15}, \phi = -0.5$ corresponding to a stable solution. We note that the variation of S is quite small.

We have thus seen that it is possible to cancel the cosmological constant using the tree level sugra scalar potential. SUSY is also broken but mainly due to the auxiliary field $k = G_\phi$ since $G_T = 0$ and $G_S \approx 0$. Unfortunately, most phenomenological terms depend on how SUSY is broken and in this case it is broken via the term which we now least and was introduced with the only motivation of rendering $V| = 0$.

If SUSY is broken via a single gaugino condensate, i.e. case (II), one can use the same linear superpotential and the cosmological constant may be arranged to vanish at the minimum. The welcome difference in this case is that SUSY is mainly broken by the auxiliary field of the dilaton G_S .

INFLATION

String models are valid below the Planck scale and it should therefore describe the evolution of the universe. The standard big bang theory has some shortcomings like the horizon and flatness problems. An inflationary epoch, where the universe expanded in an accelerated way, may solve this problems. For arbitrary values of the different fields one expects V to be positive and to evolve to its minimum. In this evolution one would hope for an inflationary period. However, it is difficult to obtain an inflationary potential in string models due to the dynamics of the dilaton field S [2].

The interaction of the dilaton field is very much constraint and the superpotential W is independent of S perturbatively but it may acquire a non-trivial superpotential non-perturbatively like when gauginos condense. Even in the presence of the non-perturbative superpotential when the scalar potential V evolves to the minimum of the dilaton field, the universe, keeping all other fields fixed, does not

go through an inflationary period. At the minimum, SUSY is broken and for vanishing v.e.v. of the chiral fields, the vacuum energy is negative and of the order of Λ^4 but as we have seen in the previous section it is possible to have SUSY broken with vanishing cosmological constant. However, in string theory there are many chiral matter fields and its potential may drive an inflationary potential [3]. The condition that these potential terms do not destabilize the dilaton field yields some strong constraint on the magnitude of these terms. Nevertheless, it is still possible to have a potential that inflates enough to solve the horizon and flatness problem. The constraint on the magnitude of these potential terms sets an upper limit on the density fluctuations which is of the order of magnitude as the observed by COBE [3].

A possible picture is that of a universe that starts with random values of the different fields (dilaton, moduli, chiral matter fields). The universe cools down and it evolves in a standard non-inflationary way until S and T are stabilized. Below this scale, other fields, like the chiral matter fields, could drive an exponentially fast expansion of the universe as long as its potential does not destabilize S and T . So, we expect that the universe arrives at an inflationary period naturally when the fields roll down to their minimum and the inflationary conditions are first met.

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